Parametric study of friction model for a reciprocating compressor

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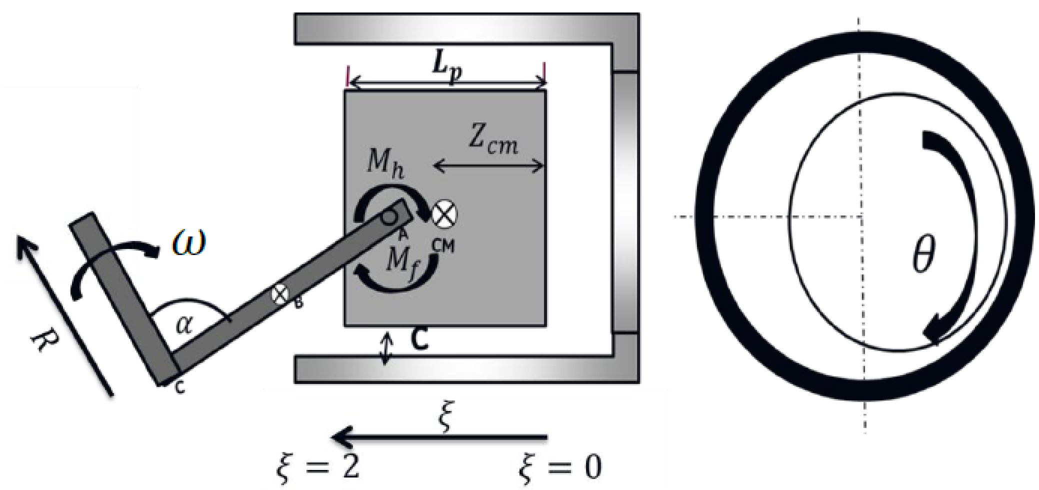
INTRDOCUTION

- Reciprocating Compressors
  - Though the desired motion of the piston is purely axial, imbalance of forces are huge source of friction
  - Estimation of friction force and associated losses in critical in design of a compressor and its performance prediction.
  - Novel solution approach is presented



Ref: Prata, A. T, Fernandes, J. R. S., Fagotti, F., 2000, Dynamic Analysis of Piston Secondary Motion for Small Reciprocating Compressors, *Journal of Tribology,* vol 122, p. 752-760

EQUATIONS OF MOTION

$$\frac{\partial}{\partial\theta}\left(h^3\frac{\partial P}{\partial\theta}\right)+\frac{\partial}{\partial\xi}\left(h^3\frac{\partial P}{\partial\xi}\right)=-12\mu R^2\left(\frac{V_p}{2R}\frac{\partial h}{\partial\xi}-\frac{\partial h}{\partial t}\right)$$

$$h=c\left\{1-\left[\varepsilon_t-(\varepsilon_t-\varepsilon_b)\xi\frac{R}{L_p}\right]cos\theta\right\}$$

$$F_h=-\int_0^{L_p}\int_0^{2\pi}P(\theta,z)Rcos\theta d\theta dz$$

$$M_h=-\int_0^{L_\mathrm{p}}\int_0^{2\pi}[pP(\theta,z)Rcos\theta](z_p-z)d\theta dz$$

$$F_f=-\int_0^{L_\mathrm{p}}\int_0^{2\pi}\left(\frac{h}{2}\frac{\partial P}{\partial z}+\mu\frac{V_p}{h}\right)Rd\theta dz$$

$$M_f=-\int_0^{L}\int_0^{2\pi}\left(\frac{h}{2}\frac{\partial P}{\partial z}+\mu\frac{V_p}{h}\right)Rcos\theta Rd\theta dz$$

F_f	*Viscous friction force*
F_h	*Hydrodynamic force*
L_p	*Piston Length*
M_h	*Hydrodynamic moment*
M_f	*Viscous moment*
R	*Piston radius*
c	*Piston cylinder radial clearance*
h	*Oil film thickness*
p_{cyl}	*Cylinder pressure*
t	*time coordiante*
v_p	*Piston velocity*
z	*Axial coordinate along piston length*
Z_p	*Axial distance from piston top to wrist pin*
$\varepsilon_t, \varepsilon_b$	*Dimensionless top & bottom eccentricity respectively*
θ	*Angular coordinate along piston circumference*
μ	*Viscosity*

SOLUTION ALGORITHM

Partial Derivatives and Central difference scheme

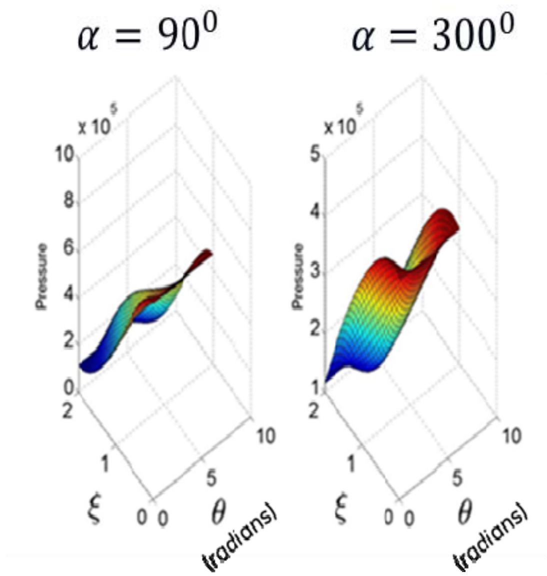
$$\frac{\partial^2 P}{\partial \theta^2} = \frac{P_{i,j+1} - 2P_{i,j} + P_{i,j-1}}{\Delta\phi^2}$$

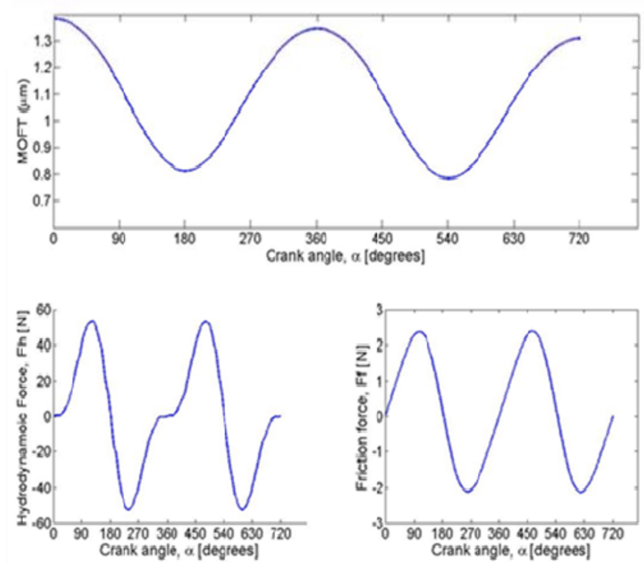
$$\frac{\partial^2 P}{\partial \xi^2} = \frac{P_{i+1,j} - 2P_{i,j} + P_{i-1,j}}{\Delta\xi^2}$$

$$P_{i,j} = \frac{C_1 P_{i+j} + C_2 P_{i-1,j} + C_3 P_{i,j+1} + C_4 P_{i,j-1} + G}{D}$$

$$\frac{\partial h}{\partial \xi} = c\ cos\theta\ \left\{ (\varepsilon_t - \varepsilon_b)\xi \frac{R}{L_p} cos\theta \right\}$$

RESULTS – Friction & Lubrication

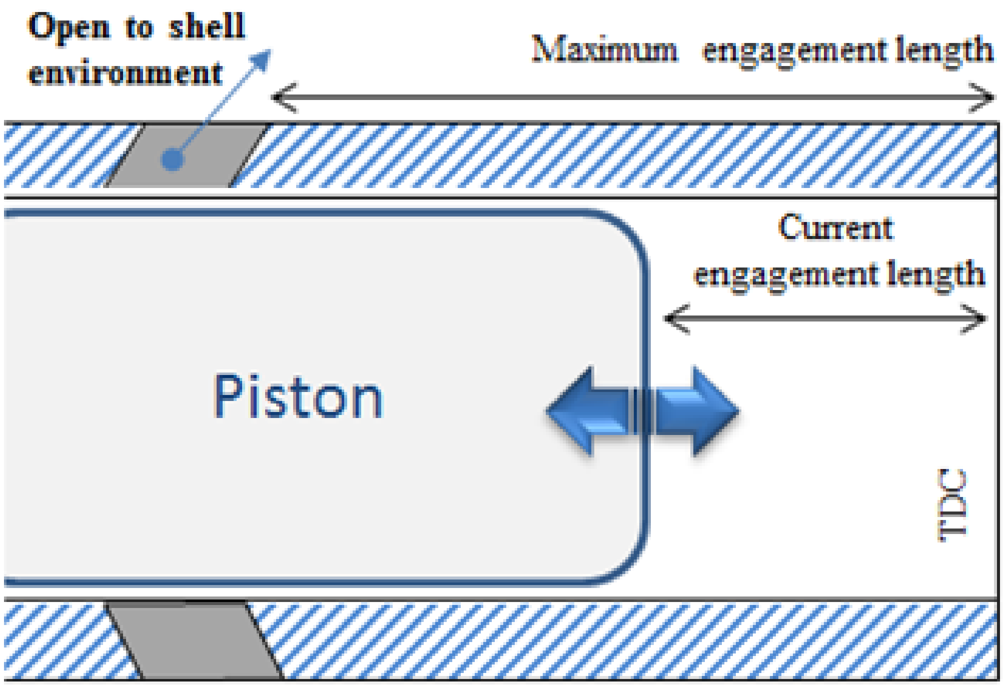




Sample simulation case

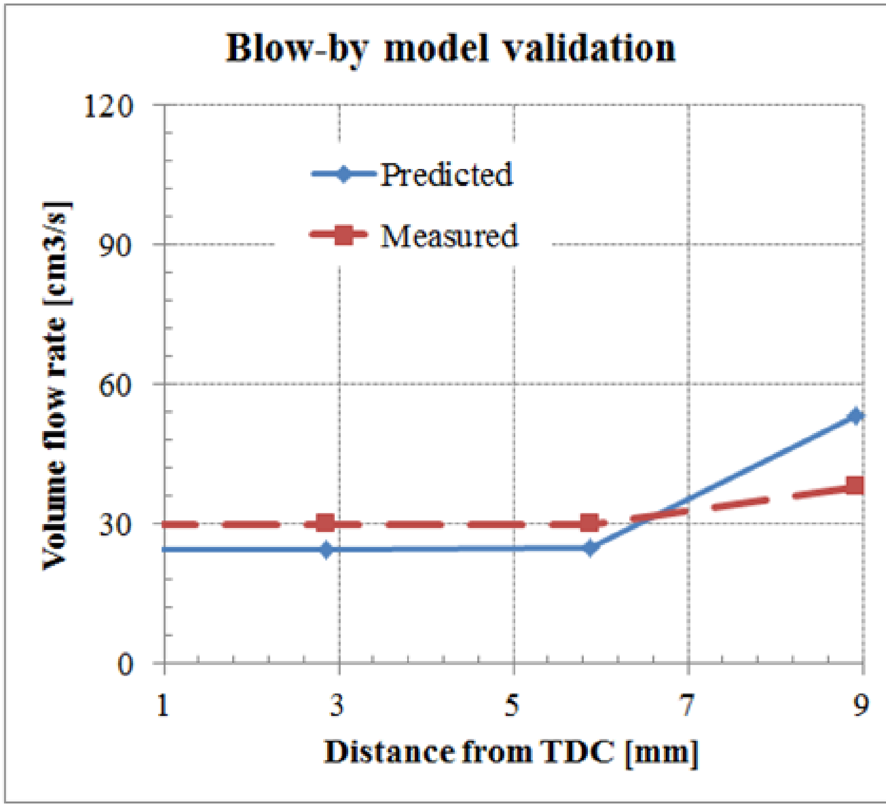
Parameter	Symbol	Value
Crank Radius	R	$10.5\ mm$
Piston-cylinder Radial Clearance	c	3μ
Crank angular velocity	ω	$3000\ rpm$
Length of Piston skirt	L_p	$2R$
Length of connecting rod	L_{AC}	$3.473R$
Mass of Piston	m_p	34.1 g
Lubricating oil viscosity	m	$3\ cP$

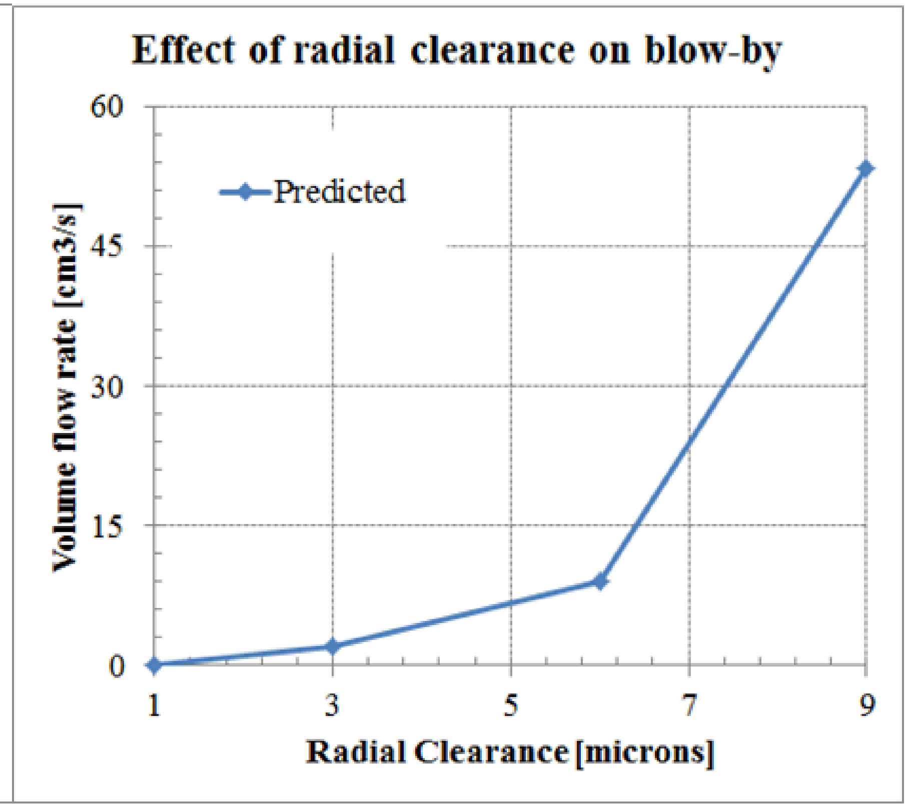
BLOW BY



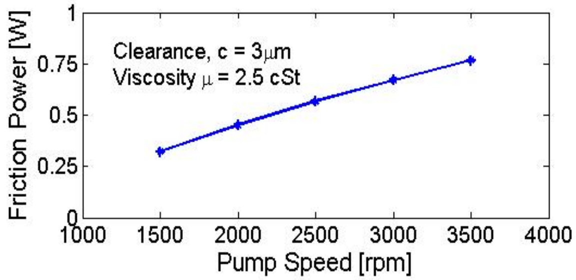
$$m_{bb} = \Delta t\, \rho_{cyl}\, (\pi\, D_p c) \left(\frac{v_p}{2} - \frac{c^2}{12\mu} \frac{\Delta p}{L_{bb}} \right)$$

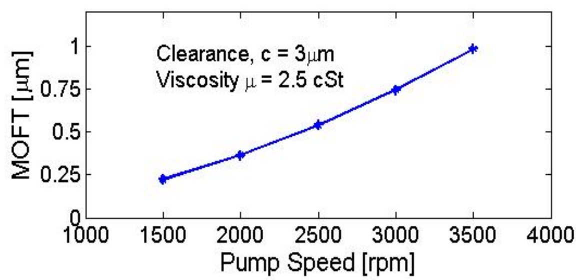
RESULTS - BLOWBY

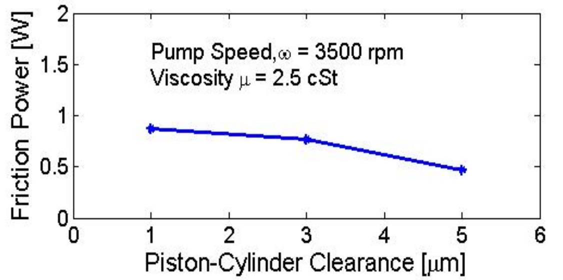


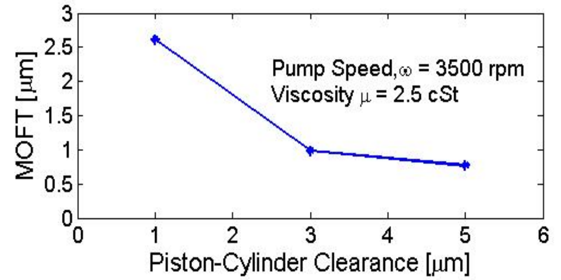


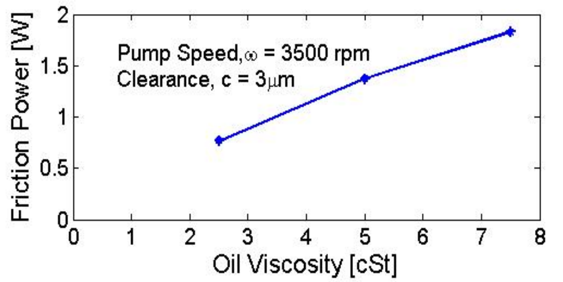
DESIGN OF EXPERIEMENTS

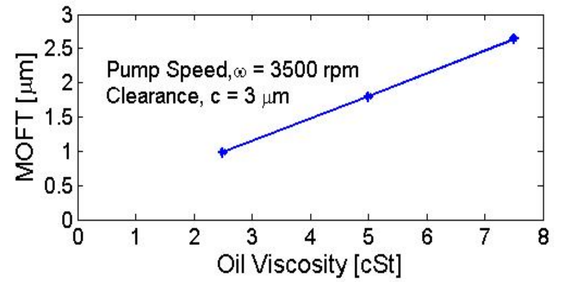












Parameter	Symbol	Units	Min.	Max.
Crank angular velocity	ω	rpm	500	3500
Piston Cylinder Clearance	c	$microns$	1	5
Lube Oil Viscosity	μ	cP	2.5	7.5

CONCLUSIONS

- Running at low rpm results in low friction power loss. Hence running at variable speed with majority of time at low speed is efficient
- During start-ups, the oil viscosity is high due to low oil temperatures and hence needs higher starting torque (or current)
- Using lower viscosity fluids (oil or gas) reduces the friction power linearly
- With increase in piston-cylinder clearance, the friction reduces and blow by increases. Hence a trade-off needs to be considered.

Appendix

Variable	Mathematical Equivalent	Variable	Mathematical Equivalent
C_1	$\left(\frac{1}{\Delta\xi^2}+\frac{3H_1}{2h\Delta\xi}\right)$	H_2	$\frac{\partial h}{\partial \phi}$
C_2	$\left(\frac{1}{\Delta\xi^2}-\frac{3H_1}{2h\Delta\xi}\right)$	H_3	$\frac{\partial h}{\partial t}$
C_3	$\left(\frac{1}{\Delta\theta^2}+\frac{3H_2}{2h\Delta\theta}\right)$	D	$\left(\frac{2}{\Delta\xi^2}+\frac{2}{\Delta\theta^2}\right)$
C_4	$\left(\frac{1}{\Delta\theta^2}+\frac{3H_2}{2h\Delta\theta}\right)$	G	$\frac{12\mu R^2}{h^3}\left(\frac{V_p}{2R}H_1-H_3\right)$
H_1	$\frac{\partial h}{\partial x}$		